Far-Infrared Heterodyne Array Receivers

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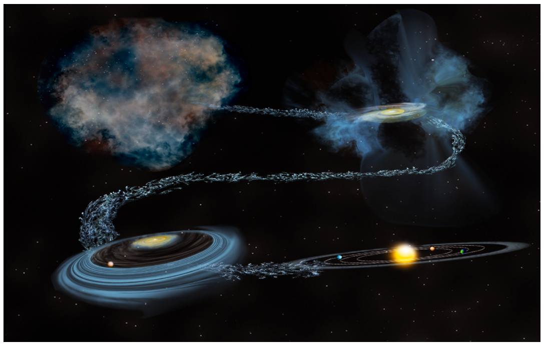
THEME: Technology Development Activity



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Artist conception of the phases of star birth (credit: Bill Saxton, NRAO)

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Executive Summary

The far-infrared/submillimeter wavelength (60 to 1000 microns, 0.3 to 5 THz) region in astrophysics is dominated by the continuum emission from dust with numerous spectral emission and absorption lines of atomic and molecular gas superimposed. *Herschel*/PACS and SPIRE photometers have determined that the dust and gas emission is filamentary in nature at all scales that have been observed [1,2,3], while the *Herschel*/HIFI receiver has demonstrated the complexity of line profiles in the far infrared, including those of the main cooling lines [4]. Far infrared spectral lines carry unique information on the cooling rate of the matter hence its ability to condense and form new systems (galaxies, stars, planets …). The processes that give rise to these structures are complex and require further investigation for a better understanding of the efficiency [4] and of the respective roles of turbulence and magnetic fields [5,6,7,8]. The same spectral range also hosts the best diagnostics of the molecular gas and water vapor content of the matter from spectral lines fully blocked by the Earth atmosphere. The information contained in spectral lines from astrophysical sources can only be revealed by observations that fully resolve the line profiles. For extended objects, velocity-resolved images are needed, to determine, for example, whether an interstellar cloud is contracting, expanding or rotating.

The only way to achieve the required spectral resolution at these wavelengths, which must be $\delta v < 0.1$ km/s or $R = f/\delta f > 3 \times 10^6$, is through the use of heterodyne receivers, in which the power spectrum at the input frequency is down-converted to a low frequency where its spectral content can be measured to very high resolution using digital techniques. Heterodyne receivers have flown on astronomical space missions including *SWAS*, *Odin*, and *Herschel*, and on solar system missions including *Rosetta*. The HIFI instrument on *Herschel* had only a single spatial pixel in each band, and as a result, only very limited spectral line imaging was carried out. Looking towards future space missions, we can imagine obtaining large velocity-resolved images of key tracers such as the 158 μm fine structure line of ionized carbon ([CII]), which is a good measure of star formation activity, the 63 μm fine structure line of neutral oxygen ([OI]), which is an excellent probe of the conditions in regions surrounding newly-formed massive stars and is thus a measure of the feedback from these stars that helps regulate the rate of star formation.

Technology developments including lower-noise SIS and HEB mixers, local oscillator sources with much increased bandwidth and output power, low-power IF amplifiers, and compact, low-power, single-chip digital spectrometers are needed to enable the next generation of heterodyne instruments, with 100's of pixels as well as instantaneous velocity coverage of up to 1000 km/s at longer wavelengths. Array receivers are particularly important for studying extended sources such as star-forming interstellar clouds and cloud cores, for which creating an image from data obtained with a single pixel system is prohibitive in terms of observing time required.

Protostellar disks have line widths of a few km/s, but will not be spatially resolved in key tracers such as H_2O or HD that require observations from spacecraft. In order to de-convolve the observed line profiles and determine where the emission originates, velocity resolutions of ~ 1 km/s ($\delta v = c(\delta f/f)$) are essential for use in conjunction with a kinematic model of the disk (obtained from e.g., ALMA observations of CO). This unique capability is impossible without high spectral resolution**.** Indeed, for future planned space missions, such as the Space Telescope (OST) [9], a spectral resolution $>3 \times 10^6$ would be needed to resolve the complex gas dynamics in individual star forming regions. **Heterodyne spectroscopic instruments are currently the only practical technical approach for obtaining velocity-resolved spectra in the far infrared. Moreover, to produce the large-scale maps of molecular clouds envisioned for future missions, large-format (100's pixels) array receivers are required.**

Key Science Goals and Objectives:

A number of key questions in astronomy require very-high-resolution spectroscopy to resolve, i.e., how do stars form?; how do circumstellar disks evolve and form planetary systems?; what are the flows of matter and energy in the circumgalactic medium?; what controls the mass-energy-chemical cycles within galaxies?; and how is water distributed in our Galaxy? The velocity structure of atomic and ionized gas associated with dense regions remains largely unknown, and can only be obtained through $R>10^6$ spectroscopy. Trying to trace the star formation rate using fine structure lines is extremely risky without being able to velocity resolve the emission. The reason is that in addition to the emission from the dense material heated by the newly-formed stars, the line of sight may include low-excitation material that is not involved in the star formation process, but which can absorb the signal from the more distant source of interest. The result can be a serious error in determination of the spectral line emission of interest. This is shown in the following two figures. Fig. 1 shows a spectrum of [CII] towards the massive star-forming region W49N. We see that the line profile has a strong emission component, but which itself is severely affected by self-absorption from less excited carbon ions, presumably in the periphery of the source. We also see two spectral lines of atomic carbon ([CI]), which appear almost totally in emission, defining the velocity range of the source. But at higher velocities we see absorption (against the continuum background) that is due to material along the line of sight.

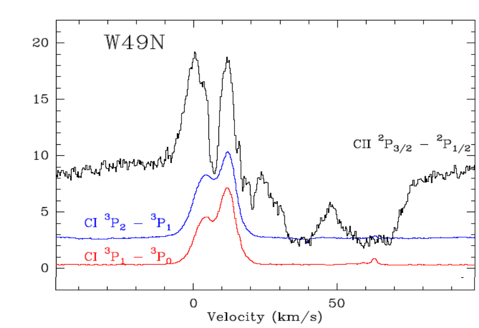

Figure 1: [CII] spectrum from W49 taken with Herschel HIFI instrument (Gerin et al. 2015).

The problem is that while this is all relatively clear with this very high velocity-resolution spectrum, if you do not resolve the line, the integrated intensity is very close to zero, due to cancellation of emission and absorption. This is seen in in Fig. 2a, a montage of spectra in the region obtained with the low-resolution (R ~ 2000) PACS spectrometer on *Herschel* that measures only the integrated intensity of the line. To accurately measure the emission from ionized carbon and determine the star formation rate in the region we need a spectrally resolved image. Such an image was obtained with the HIFI instrument and is shown in Fig. 2b. This was possible because this signal is relatively strong and the time required was quite short. But for more typical sources, this would be impossible without an array of detectors with spectral resolution greater than 10^6.

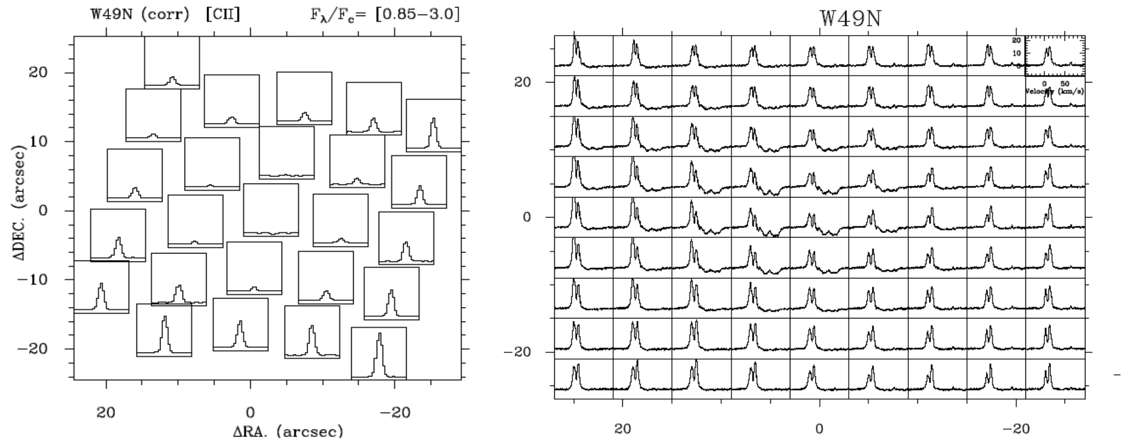

Figure 2: (a, left)) Image of [CII] from W49N obtained with PACS. The instrument does NOT resolve the line, and the profiles are actually the instrumental response. The intensity near the center is nearly zero but there is actually strong emission present. (b, right) Image of same region obtained with HIFI resolving the emission and absorption components.

An intermediate stage between an interstellar cloud and a disk containing a newly formed star and possibly forming planets is a dense core. Such regions are found to be collapsing, but the details of this process have been very difficult to unravel due to the lack of a probe of their very dense, central regions, which are very well shielded and cold before gravitational compression dominates. Such dense cores were not thought to contain gas-phase water, but more recently theoretical models suggested that some water could be kept in the gas phase by desorption of ice from grain surfaces by UV photons produced by cosmic ray destruction of H_2 molecules.

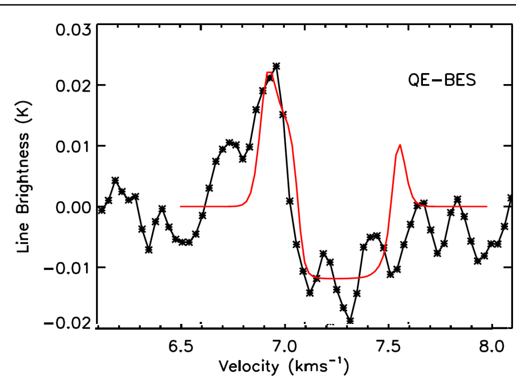

Figure 3: Spectrum of H2O from dense core L1544. The red curve is spectrum produced by theoretical model of collapsing core.

This process is sufficiently rapid to produce weak, but measurable water emission in one dense core observed with *Herschel*/HIFI. Fig. 3 shows the spectrum of the 557 GHz line of H_2O in the core L1544 [11]. The spectrum is exceedingly narrow, containing both emission and absorption features each having a width between 0.2 and 0.4 km/s. This inverse P-Cygni profile allowed detailed comparison with different models for collapsing cores, with only the quasi-equilibrium Bonner-Ebert sphere (indicated by red curve in Fig. 3) showing reasonable agreement with the observations. This represented a major advance in understanding the formation process for low-mass (including solar-type) stars, but even more information could be obtained from a spectral line image that could further constrain the symmetry of the collapse and allow more accurate determination of the velocity vs. radius law defining the collapse. This single spectrum required a 13.6 hr integration, so a pixel-by-pixel image would require an unacceptably large amount of telescope time; however, with a focal plane array, such a map would be entirely feasible.

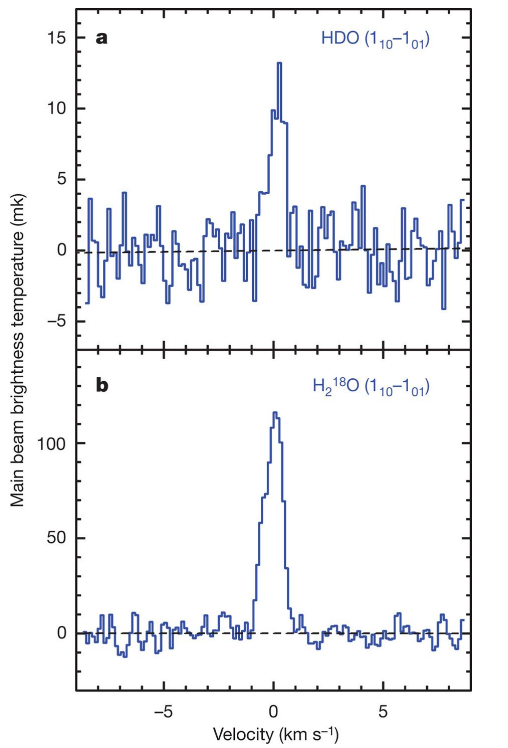

Figure 4: Spectra of $H_2{}^{18}O$ (lower panel) and HDO (upper panel) from Comet 45P/Wirtanen. Note the extremely narrow line width of the HDO emission.

A final example of the critical importance of high spectral resolution is the study of molecules in cometary comae. This is valuable for tracing the origin of the Earth's water. Comparing the D/H ratio measured in ocean water with that in comets by observing HDO/$H_2{}^{18}O$, for example, is one way to determine the contribution of comets to Earth's water. This was done recently by Lis et al. [12] for comet 46P/Wirtanen, as shown in Fig. 4. Here we see that the HDO line width is just over 1 km/s. In some comets the H_2O line width is greater, and detailed modeling of the line profile can be used to derive properties of the coma surrounding the nucleus of the comet, as well as accurately determine the amount of H_2O present for comparison with HDO.

Comets actually become extended objects when observed with large submillimeter telescopes; with Herschel's 3.5m diameter reflector, the emission from some comets was resolved. Here, the availability of a focal plane array would have been valuable beyond the savings in observing time – since the emission from comets can vary on timescales of hours, making an image with simultaneously-obtained data will be more accurate than one built up pixel-by-pixel. Having an array also allows observation of the emission from H_2O away from the center of the comet, where the optical depth is smaller and so more accurate measurements of the isotopic abundance ratio can be obtained.

The key goals and objectives of this activity are to achieve detector systems with the following capability:

1) Very high spectral observations of 0.3 km/s to 0.03 km/s i.e. R = f/δf of 10^6 to 10^7 to trace the velocity structure of water in starless cores and young disk around protostars, for example.
2) A frequency observing range to cover at least the main water lines (557, 988, 1113, 1661, and 1670 GHz) and those of its isotopologues (509, 548, 552, 894), together with the HD line (2675 GHz), is required for the water trail. The [CII] line (1901 GHz; 158 μm) is a valuable tracer of the rate of star formation and of the evolution of interstellar atomic diffuse to dense molecular clouds in which new stars form. The fine structure lines of [NII] at 1461 and 2459 GHz (205 and 122 mm) are required to probe ionized regions and measure the electron density there. [OI] at 4746 and 2060 GHz is a critical tracer of the photodissociation regions around massive young stars. OH, CH, CO, SiO, HCN, and Al-, Ti-, Fe-, Mg-, and Ca-bearing molecules and

the key molecular ions ArH^+, OH^+, H_2O^+, H_3O^+, $HCl^{+,}$ and H_2Cl^+ (with major transition lines in the 500–3000 GHz range) are also desired to probe the cosmic ray ionization rate and the essential physical and chemical processes that determine the structure of the interstellar medium. Desired frequency range is 500-600 GHz; 880-1200 GHz; 1660-1920 GHz; 2060-2700 GHz; and 3000-4750 GHz.

3) An instantaneous frequency bandwidth of 0.5 to 8.5 GHz is required. This is equivalent to ~500 km/s at 4.7 THz more at lower frequencies. At least 500 km/s bandwidth is desirable to cover the different velocities along the line of sight across a spiral arm.
4) 5 sigma sensitivities of at least 10^{-19} Wm^{-2} for 1h integration time at $R=10^6$ resolution.
5) Map a 10'x10' area of the sky with a < 4" beam at 1.9 THz (ionized carbon line) with 0.1 K temperature sensitivity in under an hour.

How to Meet Key Science Requirements

To achieve the above-mentioned science goals requires a concerted technology development effort for high-resolution spectrometers. It is difficult to achieve spectral resolutions of 10^5 or greater with direct detection systems, and higher resolution requires larger and larger physical sizes for a given design. Reaching 10^6 in space, given constraints of volume and mass, is essentially impossible. Heterodyne architectures solve that problem, making it straightforward in a physically compact system to reach 10^7 if necessary, with great flexibility in resolution, frequency range, etc. Unlike the direct detector systems, heterodyne pixel sensitivity is limited by quantum noise and we are already approaching a few times this fundamental limit. This limitation can be overcome with either larger telescopes, or with large arrays of detectors, which can decrease effective integration times by orders of magnitude. Large telescopes in space are extremely expensive and deployable structures have a very low TRL. HIFI already demonstrated single pixel detection with close to quantum noise. The next frontier is multi-pixel heterodyne array receivers, which is the subject of this white paper.

To-date only single pixel (albeit dual polarization) heterodyne receivers have flown in space. This has been a major limitation for mapping large sources or conducting galactic plane surveys on missions like HIFI. The need for array receivers is obvious by calculating integration time requirements for any large-scale mapping. Assuming a 500 K (DSB) system noise temperature at 1.9 THz, velocity resolution of 2 km/s, a temperature sensitivity of 0.025 K requires 126 s of integration time. Thus, a beam-sampled map with a 3.9" beam from a 10-m diameter telescope over a 10'x10' area will contain ~24,000 samples and total time ~1100 hours (with nominal 1.3 overhead factor). **Even for such limited mapping, single pixel receivers are inadequate, and future heterodyne systems must be based on multi-pixel (~100's of pixels) architectures. The need for multi-pixel system requires development of processes, procedures and techniques that can result in robust cost-effective systems for space telescope. Besides drastically increasing the pixel count, it is also highly desirable to have broadband receivers that provide a drastic increase in science return and only require modest amount of resources such as mass and power.**

Technology Overview:

Mixers

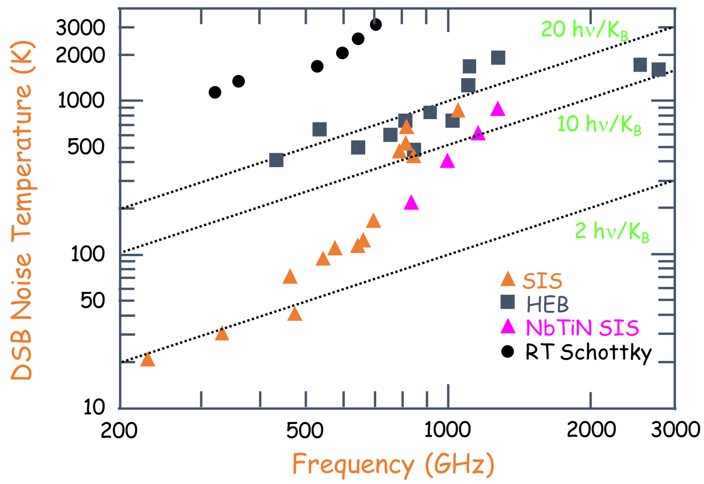

Figure 5: Next generation of submillimeter-wave mixers should provide close to quantum-limited noise performance.

Nearly quantum-noise-limited low-noise heterodyne mixers are widely used in a number of space, air-borne and ground-based receiver systems. Superconductor Insulator Superconductor (SIS) mixers, e.g., [13][14], provide near-quantum-noise-limited performance at frequencies up to that of the superconducting band gap, and have demonstrated DSB sensitivities of ~2 *hf/k*, see Fig. 5. The SIS mixers flown on Herschel are among the lowest noise heterodyne mixers made. The intermediate frequency (IF) bandwidth can easily reach 20 GHz [15] and even higher with only modest increase in noise temperature [16]. Current materials limit the frequency of operation to approximately 1.2 THz. Hot Electron Bolometers (HEB) are the most sensitive mixers above ~1.2 THz. Recently, considerable improvements in HEB receiver sensitivity have been made [17][18][19]. Traditional HEB mixers (Nb-based) are limited to around 3 GHz intermediate frequency (IF) bandwidth. Published work with novel superconducting materials, such as MgB_2, has shown that HEB mixers with an 11-13 GHz IF bandwidth are possible [20][21][22], whereas recent results indicate on an IF bandwidth exceeding 20 GHz [23]. NbN HEB mixer development is progressing as well, with recent results [24] achieving an IF bandwidth of 7.5 GHz using NbN on GaN under-layer HEBs at around 1.3 THz. The large bandwidth is required at THz frequencies to be able to observe lines of ~500km/s width. The heterodyne instrument for the Origins Space Telescope, HERO, uses SIS mixers below 1.2 THz and HEB mixers for higher frequencies with a goal of reaching a sensitivity of 2 to 3 *hf/k*. HERO will fly focal plane arrays with 9 mixers each. Large format SIS arrays up to 64 pixels have been demonstrated at low frequencies (300 GHz) [53]. At THz frequencies, 2x7 pixel HEB receivers [63, 64] have been deployed in SOFIA. For future missions what is needed is a robust and cost-effective way of producing quantum-limited mixer arrays with 100's of pixels. Integration of mixers with the first stage amplifiers is also an important for large arrays [25].

Local Oscillator

Local oscillators are a critical item, as they need to be tunable over a very wide frequency range, reach high frequencies, pump many pixels, and have low power consumption. Schottky diode-based frequency multiplier chains have made considerable progress recently [27][28][29]. By utilizing high-power GaN amplifiers at W band and power-combining multiplication technology in the submillimeter-wave range, more than 1 mW of power has been demonstrated at 1.6 THz

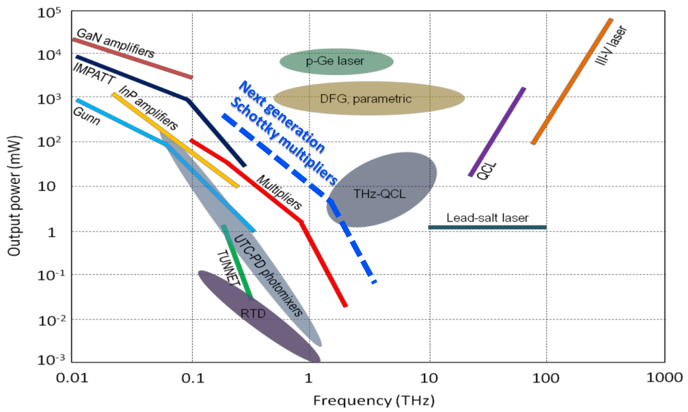

Figure 6: A number of technologies can provide the LO sources needed for array receivers. Selection of technology is dependent on the particular need and instrument design.

[30][31][32]. Traveling-wave MMIC GaN amplifier technology has already demonstrated high output power over multi-octave bandwidth up to 120 GHz. Schottky multipliers have also demonstrated full waveguide band operation (used in VNA extenders up to 1.1 THz) with somehow reduced efficiency compared to narrow band solutions. As an alternative, especially for the high-frequency channel, the quantum cascade laser (QCL) in combination with a phase grating can be used to form an LO array [33-38]. Recent QCLs have demonstrated a nearly Gaussian output beam, high operating temperature (> 45 K), and dissipate less power, so that a compact, commercial Stirling cooler can cool them. Continuous tunability can be achievable by using multimode QCL and a frequency-selective Fabry-Perot as well as a phase lock loop. HERO uses multiplier amplifier chains as a baseline, with a QCL as a backup for the high frequency channel.

Low Noise Amplifiers

Different low noise cryogenic amplifier technologies exist: InP HEMTS, SiGe BiCMOS, and superconducting parametric amplifiers. For space missions, the amplifiers not only need to have very low noise, wide bandwidth, and high stability, but also they should have a very low power dissipation (~0.5 mW per IF chain). A gain of about 20 dB is needed for the first cold amplifier, more gain can be added at slightly higher temperatures [26]. The amplifiers also need to have a good match to the mixers or alternatively, isolators need to be developed and inserted between the two.

To date, cryogenic SiGe heterojunction bipolar transistor amplifiers have demonstrated the lowest power dissipation (only 0.3mW per chain) with good noise performance (5K) albeit with an IF bandwidth of 1.8 GHz [39] and 4 GHz [40] This promising technology therefore requires further development to obtain a wider bandwidth, while keeping the power dissipation low, and a gain of at least 20 dB to avoid the degradation of the front end sensitivity.

An alternative is using the well-established InP technology, which is being employed in numerous ground-based instruments, e.g. the most recent InPs for ALMA [41], and has been space qualified for HIFI/Herschel [42]. InP cryogenic amplifiers with very good performance are now commercially available [43]. For optimal performance, they typically require around 5 mW of power per IF chain, although operation at reduced power while maintaining good performance has been described [44]. Further experiments are required to investigate their stability and reproducibility at such low power levels.

Parametric cryogenic amplifiers are capable of much lower power dissipation with noise performance approaching the quantum limit [45][46], but they need microwave pumping, which adds complexity. These devices are still to be demonstrated in practical ground-based radio astronomy receivers and are currently at a low TRL level.

Backend Spectrometers

Array receivers will require 100's of low-power backends, each with 8 GHz bandwidth. Traditional approaches such as filter banks, AOS, and Chirp- Transform-Spectrometers (CTS) are bulky and require a substantial amount of DC power (30-40 Watts). FPGA/ASIC-based solutions are currently being developed by European consortiums, while ASIC-based system-on-chip (SoC) architectures are being developed in the US with the purpose of providing low-power backends for array receivers. A 3 GHz bandwidth CMOS chip based on 65 nm technology has already been demonstrated [47][48]. This single chip backend can support 4096 channels and requires only 1.65 Watts.

To achieve a resolution of 10^6 to 10^7 the 1000 channels need to be configurable to cover more or less IF bandwidth, depending on the observing frequency. This translates into a resolution bandwidth between 4.7 MHz (for [OI] at 0.3km/s resolution) and 50 kHz (for the 557 GHz water line at 0.03 km/s). We allocate 1W power consumption to each 8 GHz backend. The 4-bit digitization (as used for ALMA) is sufficient. CMOS-based spectrometers are advancing quickly with the telecommunication industry and are predicted to reach the required bandwidth and power within a few years. Current versions have 6 GHz bandwidth, are extremely lightweight (<120 gm), and require little power (< 1W) per backend 47. An autocorrelation spectrometer (ACS) is another viable option, as it has been used already in space missions (ODIN), balloon mission TELIS, and low power ASIC versions are becoming available [50]. The goal is to have backend spectrometers that take less than 1 W per band together with 8-10 GHz of bandwidth.

Technology Development Roadmap

Table 1 describes the SOA for multipixel heterodyne systems. Currently, methodologies are based on duplicating single-pixel architectures. A paradigm shift is needed to enable large pixel count arrays that are not prohibitively expensive and bulky.

Table 1: To date only a few pixel systems have been developed. The next generation of heterodyne instruments will require 100's of pixels.

Array Name	Frequency (GHz)	$N_{element}$	Mixer	LO Injection	Telescope	Ref	Comments
HERA	220 – 260	9	SIS	WC	IRAM 30m	[51]	
CHAMP	460 - 490	16	SIS	FG+MPI	CSO 10m	[52]	Also other telescopes
Pole STAR	810	4	SIS	ML+MPI	AST/RO 1.7m	[53, 54]	
SMART	490/810	8/8	SIS	CFG+MPI	KOSMA 3m	[55]	Dual band; NANTEN 4m
Desert STAR	345	7	SIS	CFG+DBS	HHT 10m	[56, 57]	

CHAMP+	670/860	7/7	SIS	CFG+MPI	APEX 12m	[58]	Dual Band
SuperCam	345	64	SIS	WPD+DBS	HHT 10m	[59, 60]	Also APEX
HARP	345	16	SIS	ML+DBS	JCMT 15m	[61, 62]	
upGREAT	2000/4700	14/7	HEB	CFG+WG	SOFIA2.5m	[63, 64]	Dual Band

(Notes: SIS Superconductor-Insulator-Superconductor ; HEB Hot Electron Bolometer; WC Waveguide coupler; FG Fourier Grating; MPI Martin-Puplett Interferometer; ML Meander Line; CFG Collimating Fourier Grating; DBS Dielectric slab Beam Splitter; WPD Waveguide Power Divider; WG Wire Grid beam splitter; BT Image rejection by Backshort Tuning; MZI Mach-Zender Interferometer)

Sustained support and effort is needed for heterodyne arrays to mature for deployment in space instruments. Support for developing compact LO systems with > 50% bandwidths, mixers with close to quantum limit sensitivities, and backend systems that provide low-noise and low-power are key components that can provide immediate impact. Advanced integration technologies such as silicon micromachining and 3D microwave wafer-level integrations along with novel device and circuit concepts will usher in the next frontier of high-resolution submillimeter-wave heterodyne arrays with 100's of pixels that can be deployed in space.

Organization, Partnerships, and Current Status:

Research and development in this field is carried out world-wide and there is no clear organizational setup to foster partnerships and collaborative efforts. Most of the funding comes from national space funding agencies which are fragmented with no single agency having enough resources to develop all of the components/technologies described above. However, at the individual scientist/technologist level there are often strong collaborations. Recently, a heterodyne instrument for the OST was investigated by such a team. The team was led by Dr. Martina Weidner and included participants from Europe as well as the US. The Heterodyne Instrument for the Origins Telescope (HERO) is envisioned as a multi-band multi-pixel instrument that can provide simultaneous measurements for multiple signals. Because of cost restrictions of the overall satellite mission, HERO is currently a low risk upscope option complementing and enhancing the baseline instrument suite (see separate APC White Paper for Origins). The frequency band of interest is from 486 to 2700 GHz (617 to 111 μm) continuously with two polarization and 9 pixels but in a minimum number of bands. HERO will be the first heterodyne focal plane array receiver designed for a space project and covers wider frequency range than any existing or prior heterodyne receiver. As satellite resources are limited this requires the use of innovative technologies to drastically reduce the heat dissipation, mass and the power consumption of the receiver subsystems and components. Optics and Local Oscillators have to be developed for a very wide Radio Frequency (RF) bandwidth (45%) while maintaining excellent characteristics, low loss for the optics, and high power output created at high efficiency over a wide bandwidth for the LOs. Mixers, low noise amplifiers and ASIC spectrometers have to have large IF bandwidth (> 6 GHz) for observation of complete line profiles. The sensitivity of the mixers needs to be increased, the low noise amplifiers need to dissipate very little power (< 0.5mW) and have low noise (< 4K), and the spectrometers have to be very power efficient while covering many GHz bandwidth with MHz resolution (<1W/ 6GHz).

Schedule:

Figure Development schedule. As with any research and development work there may be new discoveries and the schedule cannot be fixed in detail at this stage.

Current state of the art for ground and airplane observatories is 10's of pixels, especially at frequencies greater than 1 THz, but only 1 pixel for space missions. With adequate funding it would be possible to increase the pixel count by a factor of 10 to 100 in ten years.

For space missions it is essential that the components are light, low volume and most importantly have low power dissipation. For 100s of pixels easy and reliable fabrication and simple integration are also indispensable. The development plan therefore has 3 steps: in the first step an individual pixel needs to be designed, in the second step the component needs to be adapted for an array of 100s of pixels and in a third step the different components should be integrated and a prototype array receiver fabricated and tested.

Cost Estimates:

This technology development activity will require sustained funding of around $5-10M/yr for over 10 yrs.

Research and development activity	Estimated Cost over 10 years (in M$)
Optics Development	10
Mixers for Focal Plane Arrays	30
Local Oscillators for Arrays	30
Intermediate Frequency and Amplifier integration	15
Backend Development	15
Large Scale Prototype Array Demonstration	10
Total	110

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